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An Evaluation of Water Quality at Fort Monmouth, New Jersey, Using the EPANET Model

by Thomas M. Walski, Stephen J. Draus,
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Final report

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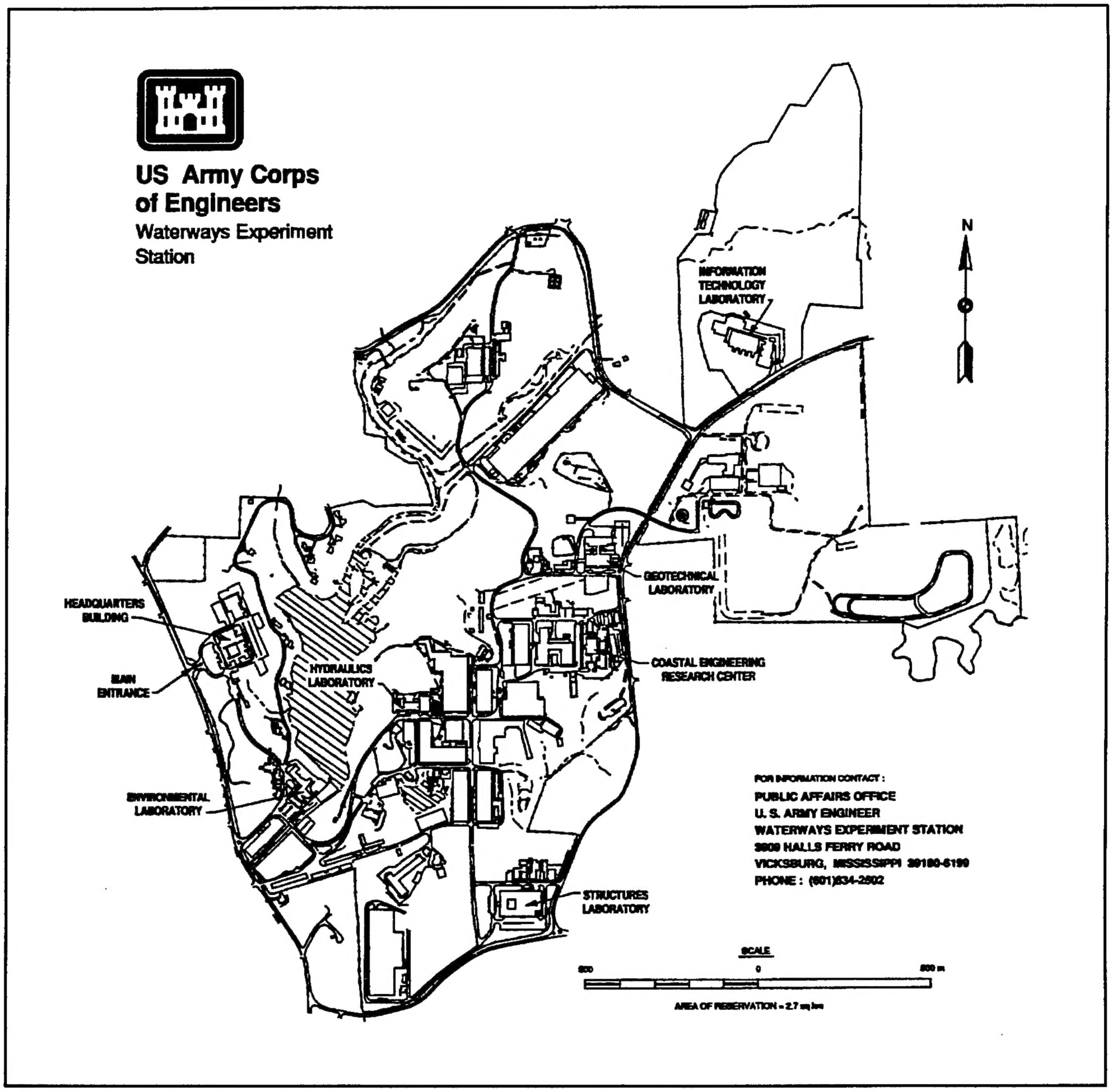

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Preface

This work reported herein was conducted for the U.S. Army Directorate of Public Works and the U.S. Army Center for Public Works. Funding was provided by the Facilities Engineering Applications Program (FEAP) of the U.S. Army Corps of Engineers. Technical Monitor was Mr. Malcolm McLeod of the Center for Public Works, Alexandria, VA.

This report was prepared by Dr. Thomas W. Walski and Mr. Stephen J. Draus of Wilkes University, Wilkes-Barre, PA. Dr. Walski was contracted to perform the work as a Short Term Analytical Service under the Army Research Office's Scientific Services Program administered by Battelle in Research Triangle Park, NC. Mr. Draus was an employee of the U.S. Army Engineer District, Philadelphia, and was assigned to this project under an inter-Army transfer.

The project was managed by Dr. Paul R. Schroeder, U.S. Army Engineer Waterways Experiment Station (WES). Technical reviews were provided by Dr. Barry W. Bunch, WES, and Dr. Stephen M. Maloney, Construction Engineering Research Laboratories. The work was performed under the general supervision of Mr. Norman R. Francinques, Chief, Environmental Engineering Division, and Dr. John W. Keeley, Director, EL.

The point of contact at Fort Monmouth was Mr. Mike Maier, Deputy Director of Public Works. The project was coordinated by Mr. Ormand Hyers of Contract Management Branch. Assistance with fieldwork was provided by Mr. Bill Thorpe and Mr. Greg Foy of E-systems. Chlorine die-off data were provided by Mr. Brian McKee of E-systems. Ms. Carol Storms, Water Quality Superintendent of New Jersey American Water Company, provided data on the New Jersey American system.

This study followed up on an earlier study conducted during 1990 by Mr. Wayne Sharp, formerly of WES. Some of Mr. Sharp's unpublished data were used in this report.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision unless otherwise indicated by other documentation.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	liters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (force) per square inch	6.894757	kilopascals
square miles	2.589998	square kilometers

1 Introduction

Background

Today's water treatment technology generally produces high-quality drinking water. Maintaining good-quality water within water distribution systems can be a problem because drinking water quality tends to deteriorate in water pipes. One concern is loss of disinfectant residuals. Disinfectant residual losses are caused by long travel time durations, which allow reactions of the disinfectant with pipe walls and within bulk fluid to become significant.

This study demonstrates how the computer program EPANET (Rossman 1994) was used to analyze alternatives for improving the water quality in water distribution systems. The program was developed by the U.S. Environmental Protection Agency's (EPA) Risk Reduction Engineering Laboratory, Cincinnati, OH. The program algorithm is "mass-transfer-based" (Rossman 1994) and was developed for predicting substance concentrations in water distribution systems. In this study EPANET was used to predict how hydrant flushing could be used to increase chlorine residuals within a water distribution system.

Fort Monmouth, New Jersey, was chosen as the location for this study because of the low chlorine residuals measured within the distribution system in the summer months. As part of this study, hydrant flushing was performed on the fort's distribution system. Hydraulic and chlorine data were obtained during the flushing tests, and these data were used to calibrate the EPANET model of the Fort Monmouth distribution system. Then, long-term chlorine residuals were analyzed. Lastly, the effectiveness of installing a chlorine booster facility was modeled.

Fort Monmouth Distribution System

Fort Monmouth receives its water from three interconnections with the New Jersey American Water Company system. These interconnections are known as Sources C, E, and F. Source C connects the Fort Monmouth system to a 36-in. cast iron main, and Sources E and F connect Fort Monmouth to a 10-in. cast iron main. Each interconnection includes a reduced pressure backflow preventer (RPBP) and a water meter. Chlorine feed equipment at each

source is currently not in use. There are two storage tanks that are currently full of water and off-line to be used only in the event of an emergency.

A large portion of the Fort Monmouth distribution system was put into service in the early to mid-1940s. Some portions of the system date back to the late 1910s, while other relatively new pipes were installed in the 1950s and later. Most of the pipes are unlined cast iron with only a scattering of polyvinyl chloride (PVC) and asbestos cement pipes. Pipe diameters range from 6 to 12 in. There are no pumps. The system average daily demand is approximately 130 gpm (0.2 MGD).

Problems

The principal water quality problem at Fort Monmouth is the difficulty in maintaining adequate chlorine residuals within the distribution system. The problem can be related to several factors: the age and physical condition of the system; the relatively low system-wide demands; low chlorine levels in the source water; and increased reaction rates, caused by higher water temperatures in the summer months, which have adverse effects on chlorine levels at the fort.

EPANET

The computer program EPANET is an extended period hydraulic and water quality simulator for water distribution systems. Pipe flows, node pressures, storage tank water elevations, and substance concentrations are calculated systemwide for multi-time period simulations. It is also capable of water age calculations and source tracing. The water quality component of EPANET can model bulk flow reactions, reactions with pipe walls, and mass transport between pipe walls and bulk flow. The program uses the discrete volume-element method for tracking water quality parameters (Rossman et al. 1993).

Overview

Chapter 2 of this report highlights a previous water quality modeling study of Fort Monmouth, describes the model input data used in this study, and describes the water supply source for Fort Monmouth. Chapter 3 presents the field flow test results collected at Fort Monmouth. Model calibration results are presented in Chapter 4. Chapter 5 covers the details of the model presentation, and transfer of the study findings to the staff at Fort Monmouth. Chapter 6 offers possible solutions to the water quality problem at Fort Monmouth, and Chapter 7 summarizes the results, findings, and recommendations of this study.

2 Model Building

Model Description

A water distribution system computer model contains two basic ingredients: the program and the input data. It is very important to have accurate and complete input data for computer modeling because the model has to mimic the actual distribution system as closely as possible for the model output to be of any practical use.

A distribution system model represents pipes, pumps, and valves as "links" and sources, tanks, and connecting junctions as "nodes." In general, a circle or a dot is the abstract symbol used to identify a node, and a line segment symbolizes a link. Nodes are placed at intersections between two or more pipes and at points where external demands are assigned. System skeletonization is common in distribution system modeling, and involves leaving out those pipes that have negligible impacts on system hydraulics. Because of the small size of the fort, there was very little skeletonization in this study.

New Jersey American (NJA) System

Fort Monmouth purchases its water from the NJA Water Company. The Monmouth System of NJA serves several boroughs and military posts, including Fort Monmouth, in the coastal region of Monmouth County, New Jersey. The Monmouth System of NJA covers an area of approximately 100 square miles.

The source of Fort Monmouth's water is generally the Neptune Water Treatment Plant, which is located 6 miles to the south near the town of Neptune City, NJ, although at times it can receive water from the Swimming River Treatment Plant in Shrewsbury Township. The main flow path to the fort includes 36,000 ft of 24-in. cast iron main and about 10,000 ft of 36-in. cast iron main. The average free chlorine concentration for water leaving the plant in August 1994 was approximately 1 mg/L. The average free chlorine concentration at a sampling point near the fort for August 1994 was 0.3 mg/L.

A summary of water quality as provided by NJA is given in Appendix A. The most noteworthy parameter is the average alkalinity, which is fairly low at 28 mg/L. This indicates that the water can be corrosive.

Input Data

Water quality modeling at Fort Monmouth

The predecessor to this study was a water quality modeling demonstration at Fort Monmouth conducted by the U.S. Army Engineer Waterways Experiment Station (WES) under the Facility Engineering Applications Program in 1990. Many of the data used in this study were taken from the 1990 study, which involved fire flow testing, internal roughness testing, and chlorine decay rate testing. Input data such as pipe lengths, node elevations, water demands, etc., used in this study were taken directly from the 1990 study. Although the actual boundary conditions (i.e., the heads at each source) were not recorded, the flow tests from the previous study were simulated using EPANET. These results are discussed in Chapter 3.

Internal roughness testing. Internal roughness testing was performed on selected pipes at Fort Monmouth in the 1990 study. This type of testing involves determining the Hazen-Williams (H-W) C-factor of a pipe. The H-W equation below relates the head loss in a pressurized water pipe to the roughness of that pipe.

$$\frac{h}{L} = \frac{10.45}{D^{4.87}} \left[\frac{Q}{C} \right]^{1.85} \tag{1}$$

where

h = head, ft

L = pipe length, ft

D = pipe diameter, in.

Q = pipe flow, gpm

C = H-W C-factor

High C-factors are associated with smoother pipes, and low C-factors are associated with rough pipes. C-factors range from about 30 for old unlined metal pipe with a high degree of tuberculation to 130 for new pipes. The C-factor test involved isolating a straight length of pipe and allowing flow through the pipe in only one direction. Flow was measured through a downstream hydrant, and pressure was measured at two points along the test pipe.

These measurements gave the head loss for the length of pipe between each pressure measuring point for a given flow rate. By inserting these values into the H-W equation, the only unknown is the C-factor, which can be solved for directly. The results of these tests are presented in Appendix B. The low values (25 to 50) indicate a high degree of tuberculation.

Chlorine decay rate testing. Chlorine decay rate testing performed at Fort Monmouth in the 1990 study included decay rates for 6- and 12-in. cast iron pipe and 12-in. PVC pipe (Sharp et al. 1991). For this type of test, selected pipes were isolated so that flow occurred in only one direction. Water was tested for free chlorine at the upstream and downstream ends of each test section. Given the pipe diameter and length and the flow through the pipe, the contact time t between the sampling points was determined. The decay constant K is left as the unknown that is solved for in the following equation.

$$C_d = C_u e^{-Kt} \tag{2}$$

where

C_d = downstream chlorine, mg/L

C_u = upstream chlorine, mg/L

e = inverse of natural log

K = chlorine decay rate, day^{-1}

t = time, days

The results of these tests are listed in Table 1. The decay constants obtained from these tests were unusually high when compared with those normally found in water distribution systems. This might be explained by the test conditions. The contact times were small, and the differences in the concentrations at the sampling points were extremely low. This resulted in a very large uncertainty in the calculated K values because the differences in the measurements made at the upstream and downstream ends of the pipe were on the same order of magnitude as the precision of the method of measurement.

Changes to input data

The biggest changes in the input data from the previous study to the 1994 study were made at the connections to the NJA system and in the general area of the flow tests. Minor head losses due to losses across the RPBPs and meters were accounted for at each source. Also, several nodes and links were added to the model in locations where flowed and residual hydrants were located. The model input data are listed in Appendix C.

Table 1
Chlorine Decay Rate Test Data

Pipe	Time (am)	Upstream Chlorine (mg/L)	Downstream Chlorine (mg/L)	Decay Rate, *k* (day^{-1})
Average *k* = -7.8				
6-in. unlined cast iron pipe	2:00	0.08		
	3:45	0.14	0.05	-6.3
	4:15	0.12		
	5:30		0.07	-9.5
	6:00		0.07	-7.3
Average *k* = -5.8				
12-in. unlined cast iron pipe	2:20	0.65		
	3:30	0.77		
	4:40		0.38	-5.4
	5:50		0.43	-6.0
Average *k* = -4.9				
12-in. PVC pipe	1:00	0.16		
	1:20	0.14		
	2:10	0.17		
	2:57		0.11	-4.3
	3:15		0.09	-5.8
	4:03		0.12	-4.3

3 Data Collection

Two trips were made to Fort Monmouth to obtain hydraulic and chlorine data. Five flow tests were performed on the Fort Monmouth water distribution system along with static pressure and background chlorine measurements. The first visit occurred on August 22-23, 1994, and the second visit occurred on September 12-13, 1994.

Static Pressures

Static pressures were measured during the first trip at the sources and at several hydrants (Table 2). Hydrant numbers were taken from the Fort Monmouth map. Source pressures were measured on both the upstream and downstream sides of the RPBPs and meters. The head loss across the RPBP

Table 2
Static Readings

Node	Hydrant or Source	Date	Pressure, psi	HGL, ft
C	Up Source C	8/22	72	174
C	Down Source C	8/22	65	158
E	Up Source E	8/22	73	183
E	Down Source E	8/22	61	156
F	Up Source F	8/22	75	190
F	Down Source F	8/22	63	162
Near 30	9-1	8/22	68	171
72	1-3	8/22	68	165
Near C	2-10	9/12	63	153
66	2-5	9/12	63	156
61	1-6	9/12	62	152
63	3-6	9/12	59	147
60	1-2	9/12	61	148
Near 56	5-1	9/12	62	152
Near 29	9-14	9/12	58	146
202	3-3	9/12	74	179

at Source C was 7 psi and at Sources E and F was 12 psi. Static pressures for the second trip were measured at hydrants only. In general, the measured static pressures varied only slightly throughout the day. The fact that these locations are spatially dispersed throughout the fort indicates that the hydraulic grade line (HGL) contours are relatively flat under static conditions. There is only one pressure zone in the Fort Monmouth system caused by the flat topography of the area.

Initial Free Chlorine Concentrations

Chlorine measurements were made using a portable HACH colorimeter. A quality control test was performed on the Hach test kit that was used for both visits to Fort Monmouth. Discussion of this test and the results, which showed very good repeatability, are presented in Appendix D. Background chlorine concentrations for both trips to Fort Monmouth were measured at the same locations where static pressures were measured. The highest chlorine concentrations measured were on the NJA side of Sources C and F at levels near 0.40 mg/L for the first trip. At all other locations virtually no chlorine was detected. For the second visit, the highest chlorine concentration of 0.25 mg/L was measured at a hydrant on the NJA system on the upstream side of Source C. No chlorine was measured above 0.06 mg/L within the fort. These data are presented in Table 3. Key factors that influence the chlorine concentrations at Fort Monmouth include time of year, total demand on the system, and the physical condition of the system.

Table 3
Initial Chlorine Levels

Node	Source or Hydrant	Date	Chlorine, mg/L
C	C	8/22	0.45
E	E	8/22	0.00
F	F	8/22	0.42
Near 83	14-24	8/22	0.00
Near 30	9-1	8/22	0.00
60	1-2	8/22	0.02
63	3-6	8/22	0.00
F	F	8/23	0.18
216	13-8	8/23	0.03
Near C	2-10	9/12	0.06
66	2-5	9/12	0.05
61	1-6	9/12	0.05
63	3-6	9/12	0.02
60	1-2	9/12	0.02
Near 56	5-1	9/12	0.05
202	3-3	9/12	0.05

Time of year

Chlorine levels vary with the seasons. This is due primarily to higher water temperatures in the summer months. Chlorine decays more rapidly in warmer months. In effect, the chlorine decay rate in water distribution systems is a function of the seasons. Figure 1 is a plot of chlorine versus time for a portion of fiscal year 1994. Water samples were measured by the Fort Monmouth Environmental Lab for chlorine at four buildings in Fort Monmouth. As can be seen in Figure 1, chlorine levels are generally higher in the winter months and lower in summer months. The low values in November 1993 may have been due to difficulties in sampling or testing. The data point from Building 270 for November was eliminated because it was an outlier point.

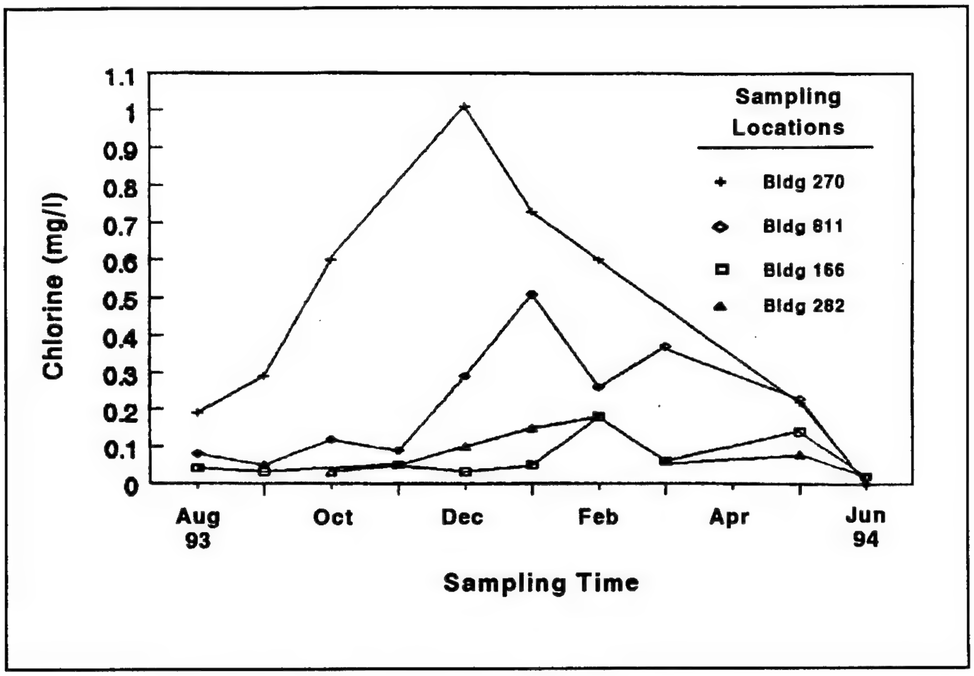


Figure 1. Seasonal variations in chlorine levels

System demands

The lack of water demands on the system at Fort Monmouth allows very little movement of water through the system, resulting in very long detention times. Figure 2 is a plot of the monthly flow at each source for a portion of fiscal year 1994. Source C is the primary source.

Monthly demands remained below 300 gpm throughout the year. The long detention times resulting from low velocities caused by the low demands allow chlorine to react with pipe walls and within the bulk fluid. This produces stale water with little or no chlorine residuals throughout large portions of the distribution system.

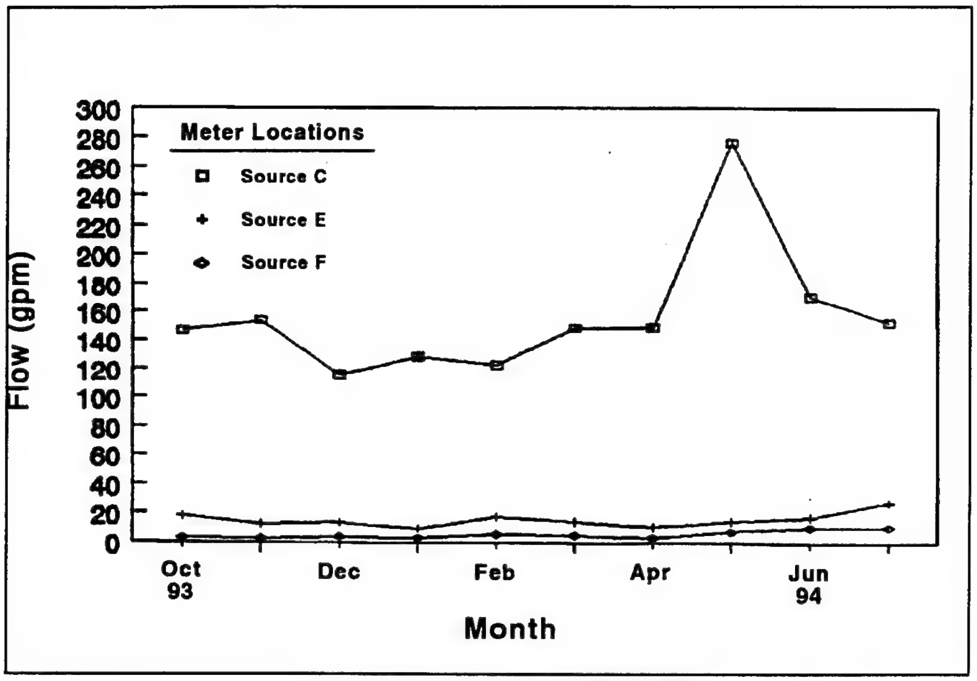


Figure 2. Monthly flow at each meter

Physical condition

Much of the distribution system at Fort Monmouth has seen over 50 years of service. The tuberculation and accumulated sediments in these pipes can impact the decay of chlorine in this system.

Flow Tests

Five hydrant flow tests were performed at Fort Monmouth. Flow Test 1 took place on August 22, Flow Tests 2 through 4 were run on August 23, and Flow Test 5 was performed on September 12, 1994. For each flow test, residual pressure measurements made at several hydrants have been used to calculate the respective HGLs. Chlorine and flow were measured over time at each flowed hydrant. These data are presented in Appendix E. Hydrant numbers and nearest node numbers are listed. See Figure 3 for node number locations.

Flow Test 1. Hydrant 3-1 (206)[1] at Riverside Avenue was flowed, and residual pressures were measured at Hydrants 3-3 (202), 3-6 (63), and 3-8 (58). The duration of Flow Test 1 was 73 min.

[1] Nearest node number is given in parentheses following hydrant number.

Flow Test 2. Hydrant 13-26 (7) near Source F was flowed for this test, and residual pressure was measured at Hydrant 13-27 (207). Also, the 12-in. pipe serving Hydrant 13-3 (11) was valved off to reduce flow from Source C for Flow Tests 2 through 4. Initial chlorine measured on the NJA side of Source F prior to the flow test was 0.18 mg/L. The duration of Flow Test 2 was 15 min.

Flow Test 3. Hydrant 13-5 (212) near the motor pool was flowed, and the residual pressures were measured at Hydrants 13-4 (217), 13-8 (216), 13-25 (209), 13-26 (7), and 13-27 (207). Chlorine was measured at Source F after Flow Test 3 at a level of 0.40 mg/L. Flow Test 3 had a duration of 68 min.

Flow Test 4. Hydrants 13-7 (214) and 13-9 (218) were flowed, and residual pressures were measured at Hydrants 9-14 (29), 13-4 (217), 13-8 (216), 13-11 (215), 13-16 (208), 13-22 (210), 13-25 (209), 13-26 (7), and 13-27 (207). Flow Test 4 had a duration of 48 min.

Flow Test 5. Flow Test 5 was performed on a second visit to Fort Monmouth which occurred on September 12-13, 1994. This test duplicated Flow Test 1. Hydrant 3-1 (206) was flowed, and residual pressures were measured at Hydrants 1-2 (60), 1-6 (61), 2-1 (62), 2-5 (66), 2-7 (64), 2-10 (Source C), 3-4 (59), 3-6 (63), 3-8 (58), 3-11 (70), 5-1 (56), and 9-14 (29). The duration of Flow Test 5 was 72 min.

4 Model Calibration

Calibration Data

Models need to be calibrated until the model output comes reasonably close to the field data. For models that have water quality capabilities, such as EPANET, it is important to note that before attempting any calibration of the water quality portion of the model, the model hydraulics should first be calibrated. The reason for this is that the velocities calculated by the hydraulic portion of the model govern the transport of the chemical substance that is being modeled.

Without calibrating the hydraulic model first, it will be more difficult to identify sources of error in the water quality model simulations. The Fort Monmouth distribution system was represented by the model in Figure 3, which was taken directly from an EPANET simulation.

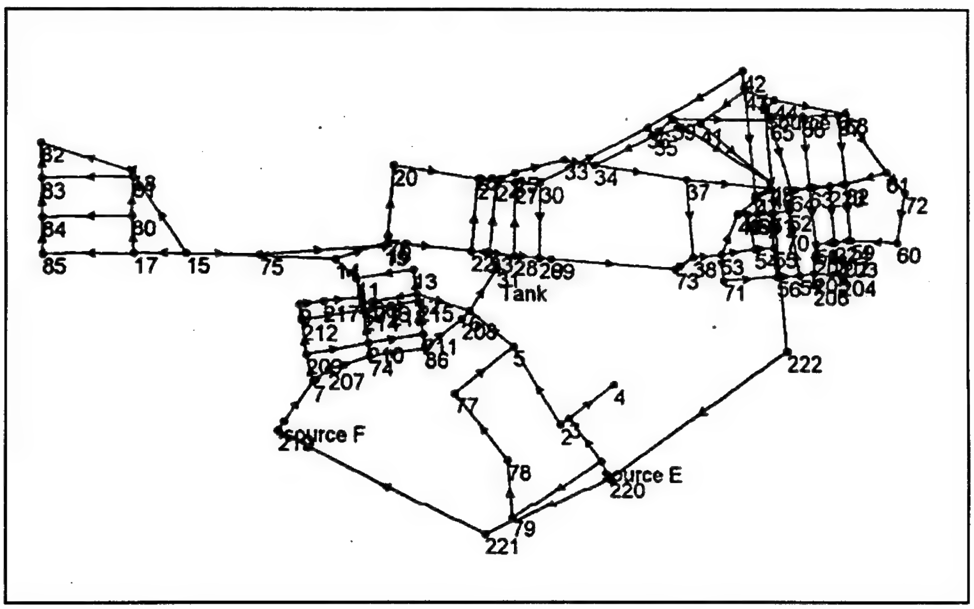


Figure 3. Map of distribution system as modeled (with node numbers)

Calibration Process

Initial estimates were made using EPANET from flow test data gathered in the earlier study at Fort Monmouth. The results of these simulations are presented in Appendix F. With the exception of the H-W C-factors, all of the input data from the previous study were used. Calibration was initiated by assigning C-factors to each pipe. Based on the average pipe age and results from the earlier C-factor tests, an initial C-factor of 40 was used for 6-in. cast iron pipe, corresponding to a roughness height of 1.52 in. This value was then used to calculate the C-factors for the other pipe diameters by the following equation:

$$C = 18.0 - 37.2 \log \left[\frac{e}{D} \right] \tag{3}$$

where

e = roughness height, in.

D = pipe diameter, in.

Because the boundary heads were unknown, this earlier attempt at calibration could not be considered complete. However, the existing model was reasonably close to the old field data. Additional field data were required to ensure that the model was calibrated correctly.

Hydraulic data collected from the five flow tests performed in August and September 1994 were used to calibrate the model further. A boundary head of 158 ft was assigned to Source C downstream of the RPBP. This value was based on the static pressures measured at that source, and it accounts for the discrete losses across the RPBP. The minor losses across the RPBPs and flow meters were accounted for by the following equation:

$$h_m = K \frac{V^2}{2g} \tag{4}$$

where

h_m = minor losses, ft

K = minor loss coefficient

V = velocity, ft/sec

g = acceleration due to gravity, ft/sec^2

The head losses across the RPBPs and observed flows were used to calculate the minor loss coefficient *K* at each source.

The model taken from the previous WES study was built upon further by adding nodes and pipes to key areas. A portion of the NJA system was added to the model. It includes a 10-in. cast iron main that is connected to the fort at Sources E and F. This main connects with a 36-in. cast iron main on Oceanport Ave. The 36-in. pipe is connected to the fort at Source C. The C-factors of the NJA pipes were then changed until the residual heads calculated by the model converged with the field data. This was used to mimic the distribution grid of the NJA system near Fort Monmouth. A comparison of residual heads measured during each flow test and those predicted by the model is presented in Table 4.

Once the hydraulics were calibrated, free chlorine residuals were modeled based on water quality field data. A "rough," uncontrolled estimate for the bulk decay constant, *Kb*, was made by measuring the change in chlorine over time for a water sample taken from Source F. A second bulk decay constant was obtained from a bottle test that was performed on a water sample taken from a hydrant on the NJA system. This test was performed at a constant temperature by the Environmental Lab at Fort Monmouth. Figure 4 is a plot of free chlorine over time for both tests. The best-fit first-order decay constant was 2 day^{-1} and 0.78 day^{-1} for the uncontrolled and controlled tests, respectively. No wall decay constant was used for this study. Chlorine decay rates had minimal impacts on changes in chlorine levels during the flow test time intervals. Chlorine decays on a time scale of days, and the flow tests were in terms of minutes. Because the model was not sensitive to these values, flushing simulations were made using the 2 day^{-1} chlorine decay rate.

Next, the flow tests were simulated. Flow Tests 1 and 5 were simulated individually. Because Flow Tests 2 through 4 were conducted in the same area and in rapid succession, these tests were simulated back to back in one model run to match what actually occurred in the field. This allowed the final conditions at the end of Tests 2 and 3 to be carried over as the initial conditions for Tests 3 and 4, respectively.

Initial chlorine residuals were assigned values of 0.00 mg/L throughout the fort for Flow Tests 1 through 4 based on the lack of measurable chlorine residual. For Flow Test 5, chlorine levels measured in the field before the test were used to extrapolate the initial chlorine concentrations in the test vicinity for the simulation. Source chlorine concentrations were held constant for Tests 1 and 5 and varied for Tests 2 through 4 to reflect field conditions. Flow test times were on the order of an hour, and the model reflected this by using minute time steps to capture the variations in chlorine concentrations.

Table 4
Hydraulic Calibration Data

Test No.	Flowed Node	Flow, gpm	Residual Node	Field HGL, ft	Predicted HGL ft
1	206	528	58	113	113
			63	122	128
			202	73	79
2	7	973	207	132	133
3	212	973	7	136	135
			207	135	135
			209	132	129
			216	128	134
			217	122	121
4	214	868	7	104	110
			29	145	135
			207	103	108
			208	145	122
			209	100	105
			210	90	104
			215	102	102
			216	89	95
			217	90	98
5	206	514	44	151	153
			56	156	149
			58	122	125
			59	144	137
			60	143	137
			61	152	146
			62	151	143
			63	128	143
			64	154	146
			66	134	147
			70	154	148
			202	78	78

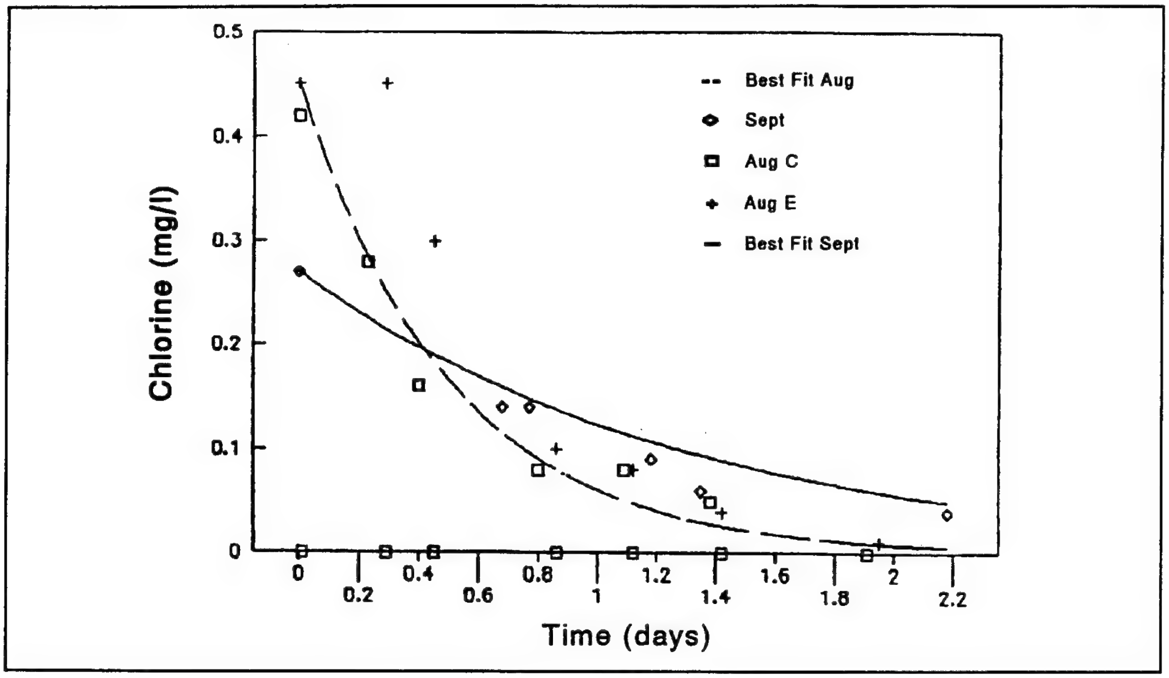


Figure 4. Plot of chlorine data

Calibration Results

Flow Test 1

For Flow Test 1, the sharp drop in the HGL to 73 ft from 158 ft at Hydrant 3-3 (near Node 202) indicated that the immediate area of the flow test was isolated in some way from either Source C or E by a closed valve or perhaps a severely tuberculated pipe feeding that area. In addition, as Figure 5 shows, the chlorine levels measured at Node 206 were very low and nondetectable for most of the test duration.

This test was simulated with Pipe 87 closed because the flow test revealed a closed valve in that pipe. Also, Flow Test 1 occurred in the afternoon. The normal demands were increased at nodes that represented water use areas that followed a work day schedule. These areas included offices, maintenance shops, and operations buildings, among others. The field and predicted HGLs are in good agreement, as illustrated in Figure 6.

From Figure 5, the model predicted that there would be no chlorine in the hydrant discharge until about 29 min into the test. The chlorine levels should have risen quickly over the last 30 min of the test. The field data show very low chlorine levels for the duration of the test. For this simulation, the model predicted the chlorine to arrive at Node 206 as a front. The field data do not reflect this. It is not known if the source chlorine levels varied during this test. It is also not known to what extent mixing affected what actually

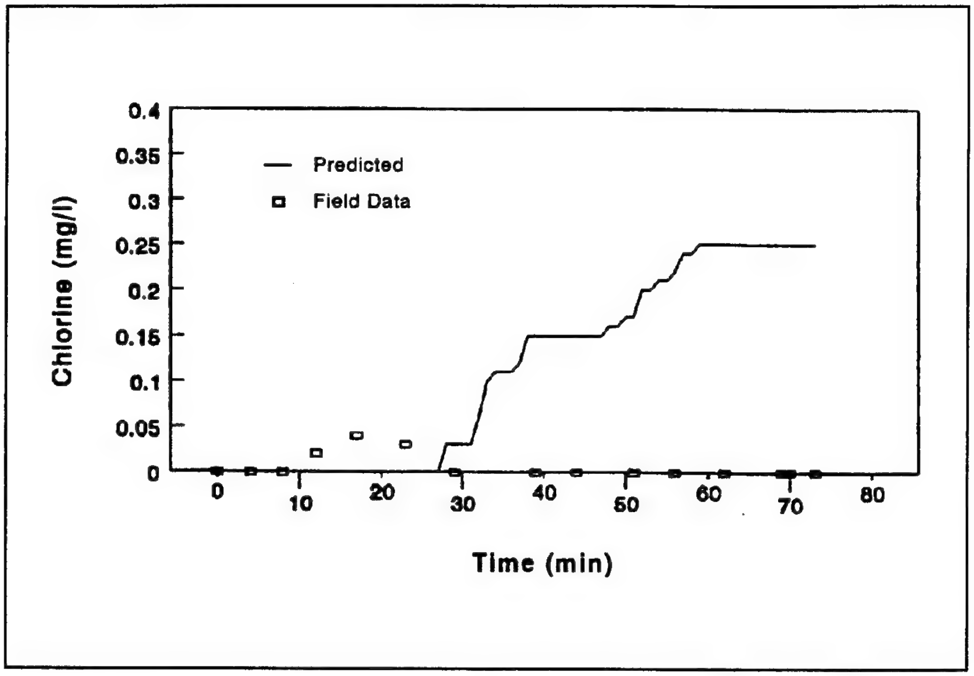


Figure 5. Comparison of chlorine over time for field and model data for Flow Test 1

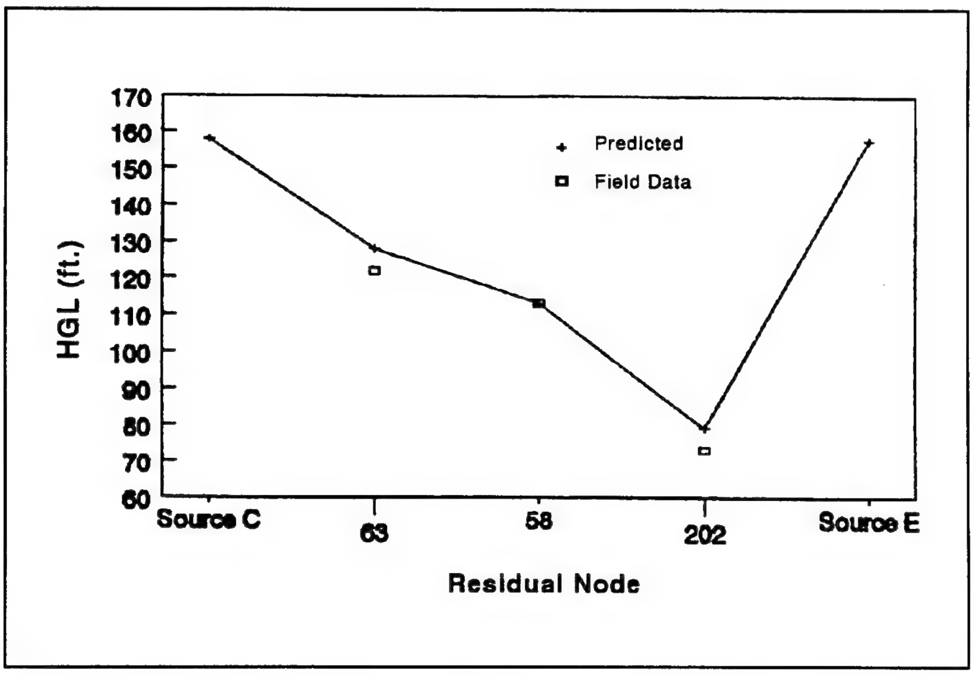


Figure 6. Field and predicted HGLs at residual nodes along a flow path for Flow Test 1

occurred in the field. Flow Test 5, conducted during the second field visit, is a repeat of this test.

Flow Test 2

Flow Test 2 was run near Source F. From Table 4, the field and model heads at the residual node agree. Initial chlorine measured at Source F prior to Flow Test 2 was 0.18 mg/L. Chlorine levels at the beginning of the flow test were not detectable. Then, a spike occurred 4 min into the test, after which the chlorine levels began to rise again. These results suggest that water was pulled in from nearby Source F during Test 2. This is illustrated in Figure 7. The chlorine levels reached nearly the same level that was measured at Source F prior to this flow test.

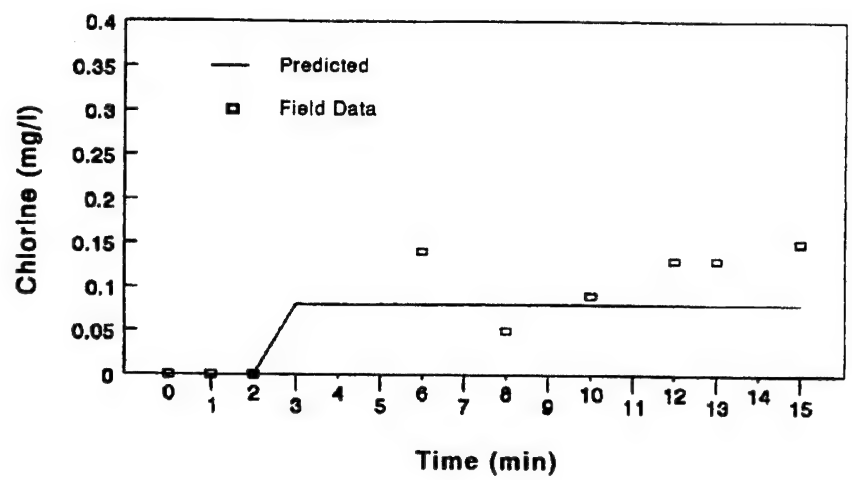
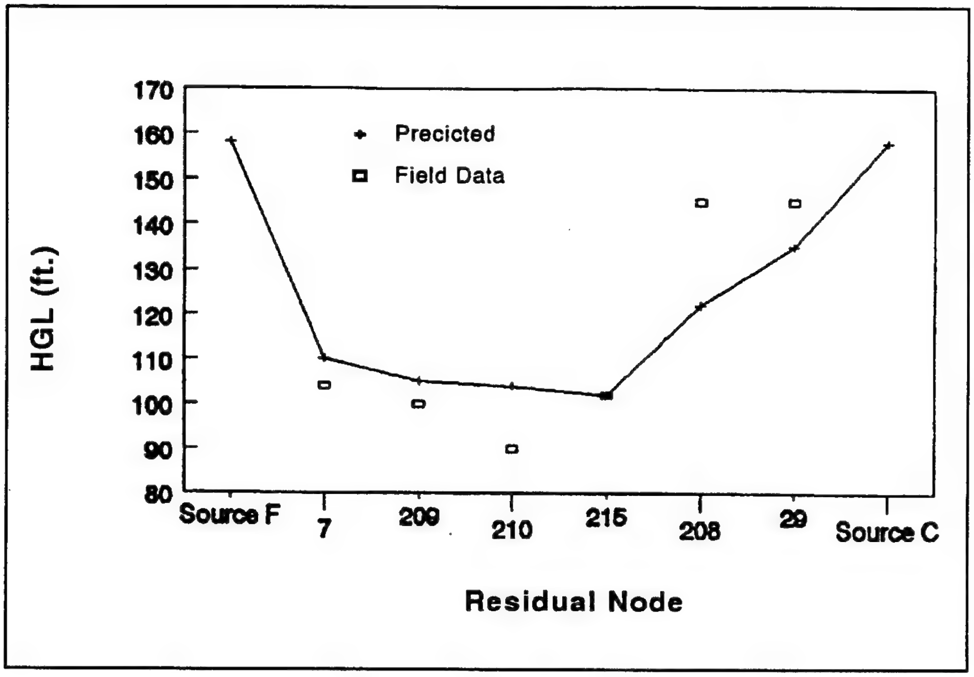


Figure 7. Comparison of chlorine over time for field and model data for Flow Test 2

The model underpredicted chlorine for most of the test. Figure 7 compares the changes in chlorine observed in the field data with the changes predicted by the model. The source concentration of 0.18 mg/L was used for this simulation. However, the values obtained from the model did not reflect the field data satisfactorily. The field data show chlorine levels gradually increasing. However, the model shows chlorine increasing sharply after about 2 min and then remaining constant for the rest of the flow test. Again, the model predicts the chlorine reaching the sampling point, Node 7, as a fairly abrupt front.

Flow Test 3

Figure 8 is a comparison of the field and predicted HGLs along a flow path for Test 3. Although the model underpredicted the head at Node 209 and overpredicted at Node 216, these differences were only about 5 ft. The predicted HGL adequately reflects the field data.



Figrue 8. Field and predicted HGLs at residual nodes along a flow path for Flow Test 3

The variation in chlorine levels measured during Test 3 might have been influenced by the chlorine levels outside the fort within the NJA system. For example, a pocket of relatively stale water may have been pulled into the fort from the NJA system during Test 3. This water then mixed with the already stale water within the fort, which resulted in the low levels of chlorine measured in Test 3. Chlorine was measured a second time after Test 3 at Source F and was found to be 0.40 mg/L. This does substantiate that chlorine levels in the NJA system did change in the time interval prior to Flow Test 2 and the end of Flow Test 3. The fact that the chlorine levels at Source F did change also makes the "stale water pocket" explanation more plausible. The model did not account for these changes (see Figure 9). The model predicted a sharp rise in chlorine 5 min into the test with chlorine levels holding steady for the remainder of the test. As with the previous two flow tests, this illustrates the importance of having good initial conditions and the significance of accounting for variations in source concentration over flushing intervals.

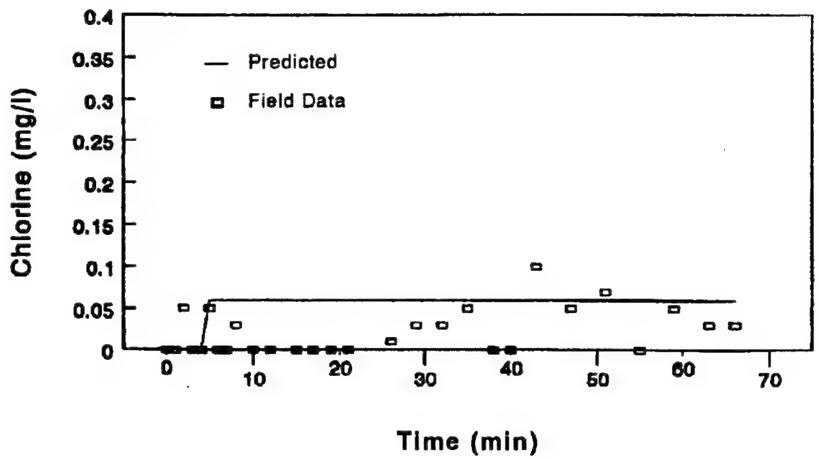


Figure 9. Comparison of chlorine over time for field and model data for Flow Test 3

Flow Test 4

Figure 10 compares the predicted and field HGLs along a flow path for Test 4. The predicted heads at Nodes 7, 209, 210, and 215 are in acceptable agreement with the field data, but the results at Nodes 208 and 29 diverge. The model seems to indicate that the heads at Nodes 29 and 208 are more influenced by Source C and less by Source E. The field data reflect that Source E has a greater effect on the conditions at Nodes 29 and 208.

A chlorine level of 0.03 mg/L was measured prior to this test at nearby Hydrant 13-8, indicating that chlorine concentrations in the immediate area of Flow Test 4 were initially very low. Within the first 19 min of flushing, appreciable chlorine levels were measured at around 0.15 mg/L. However, over the remaining 26 min of the test chlorine levels increased less rapidly. Although it is not known if or how the source chlorine concentrations varied during this test, this flow test was modeled with a chlorine concentration at Source E of 0.40 mg/L. This matched the chlorine level measured at Source F just before the start of Flow Test 4. Figure 11 compares the chlorine data measured and predicted for Flow Test 4. The field and model data are in reasonable agreement except for the last 10 min of the flow test. It is unknown if the lower chlorine measurements near the end of the flow test resulted from mixing effects within the fort or changes in chlorine levels in the source water. This gives further evidence of the need not only for good initial conditions but also for a record of source concentrations during the flow test times.

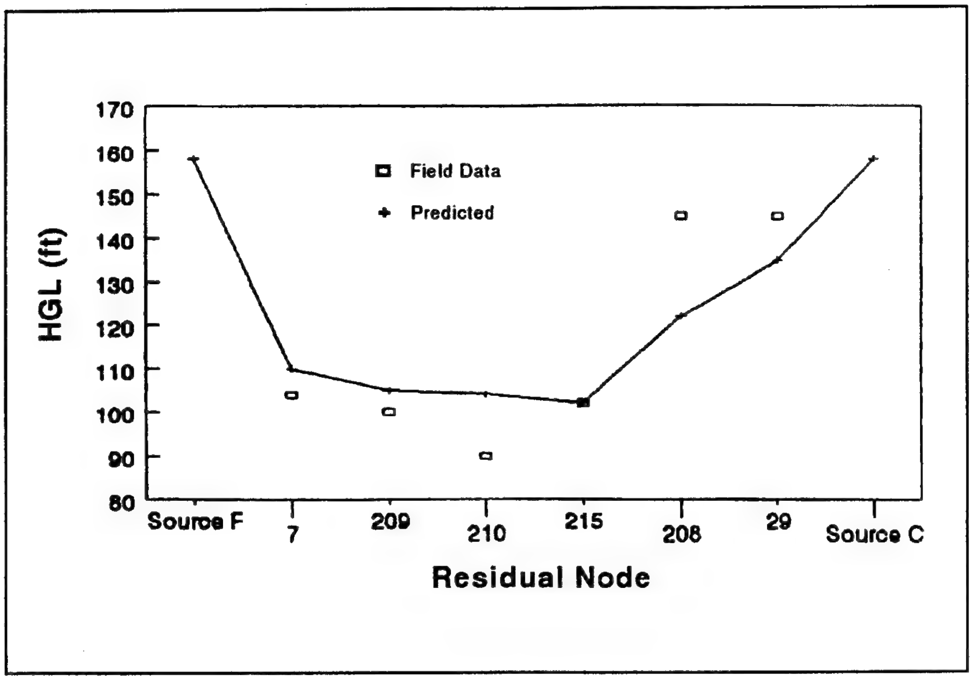


Figure 10. Field and predicted HGLs at residual nodes along a flow path for Flow Test 4

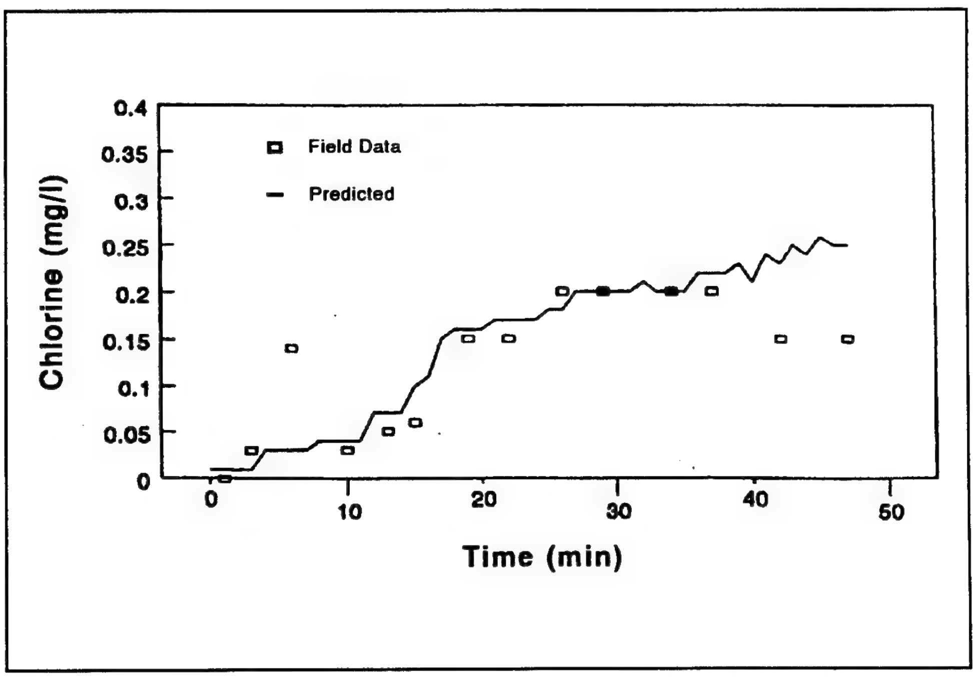


Figure 11. Comparison of chlorine over time for field and model data for Flow Test 4

Flow Test 5

Flow Test 5 occurred in the evening of September 12, 1994. This is important because the location of this test was in a residential area of the fort. For this simulation the nodal demands in this area were modified to reflect typical residential water uses for this time of day. Figure 12 compares the heads predicted and measured at residual hydrants for Flow Test 5. The model and field data agree reasonably well at all nodes except Nodes 63 and 66. At both nodes the model overpredicts by about 10 ft. Also, from Table 4, the field data show that more head loss is occurring in the pipes between Nodes 58, 63, and 66. This gives a good indication that more water is flowing through these pipes than the model is accounting for. This might be due to closed or partially closed valves within the distribution grid in this portion of the fort.

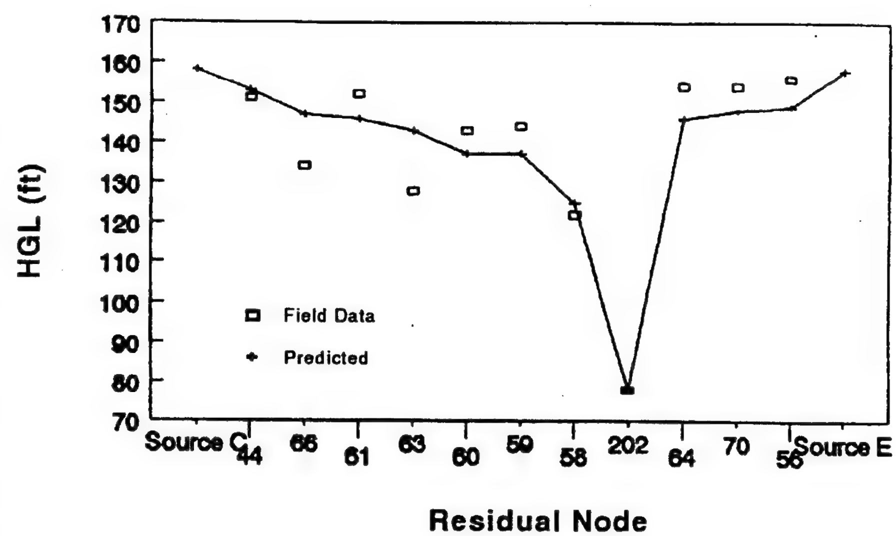


Figure 12. Field and predicted HGL's at residual nodes along a flow path for Flow Test 5

Initial chlorine concentrations were assigned to each node by interpolation between eight measurements made prior to Flow Test 5. Chlorine was measured at a hydrant on the upstream side of Source C before Flow Test 5 as 0.25 mg/L. This hydrant was 2-10, 100 ft from the meter. Chlorine was also measured on the downstream side of Source C just after Flow Test 5 as 0.12 mg/L. This hydrant was about 200 ft from the source. A constant chlorine concentration of 0.12 mg/L was assigned at Source C, because the later measurement was probably more representative of the source concentrations for Test 5. Figure 13 compares the model and field results of Flow Test 5. The predicted and field chlorine levels agree reasonably well for most of the test. However, the model predicts higher chlorine levels for the last

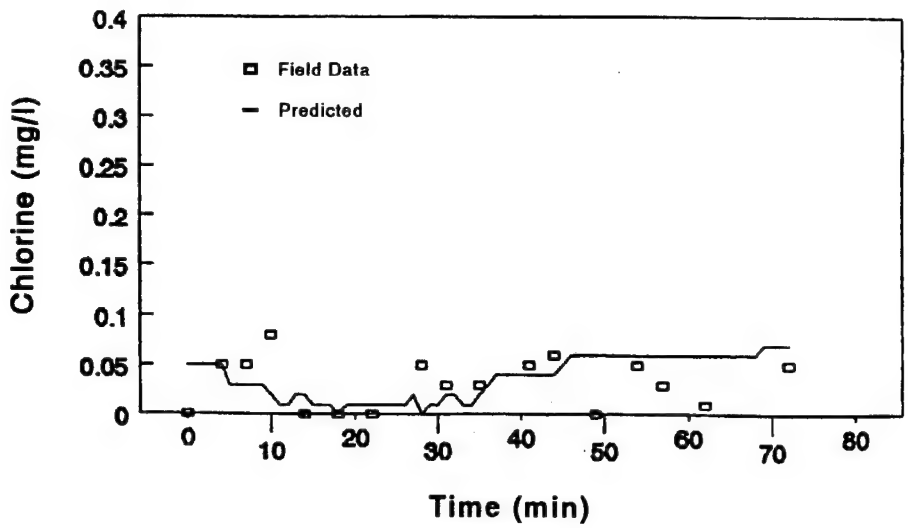


Figure 13. Comparison of chlorine over time for field and model data for Flow Test 5

15 min of the test. Again, it is not known if the lower chlorine levels measured over this time period were caused by mixing effects or changing source concentrations.

Finally, turbidity was measured during Flow Test 5. Turbidity was modeled as being directly related to pipe velocities:

$$\text{Turbidity} = f(\text{velocity})$$

Initial turbidity levels were assigned to nodes based on model-calculated velocities in the pipes. High turbidity levels were assigned to nodes whose connecting links had high velocities. Lower turbidity levels were assigned to areas with lower pipe velocities. The velocities and their assigned turbidity values are as follows:

Velocity, ft/sec	Turbidity, NTU
<0.5	10
0.5-2.0	20
2.0-3.0	30
3.0-5.0	40
>5.0	50

Turbidity was modeled as a conservative substance because, once solids were resuspended, they were unlikely to settle during the test. The simulation of Flow Test 5 tracked the change in turbidity at the flowed hydrant. Figure 14 compares the predicted and field data. The figure shows that the model predicted changes in turbidity quite well.

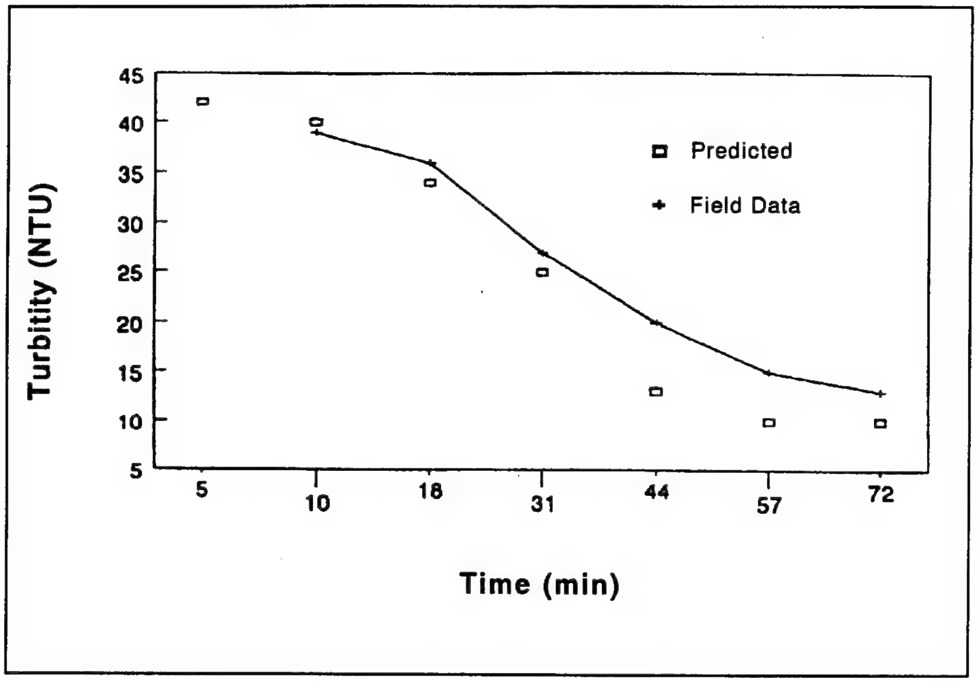


Figure 14. Comparison of turbidity over time for field and model data for Flow Test 5

5 Technology Transfer

Training

The EPANET program, input data, and a copy of the program user's manual were presented to the staff at Fort Monmouth on September 13, 1994. Also on that day, a brief training session on the use of EPANET was held for Fort Monmouth personnel.

Water Quality Modeling

This section describes the steps that need to be taken for successful water quality modeling.

Input data

Once the water quality problem to be solved has been defined and the software has been selected, accurate and complete distribution system data need to be obtained. Input data types include junction elevations, pipe diameters and lengths, pipe roughnesses, nodal demands, water tank elevations, boundary pressures, background and source chlorine levels, and chlorine decay rates. This information is already in the Fort Monmouth model.

System changes

Changes to distribution systems, such as adding new pipes and closing valves, need to be accounted for in the model when they occur. Valves can be closed in the model under the STATUS section of the input data. For more information on this option, see the EPANET user's manual.

Flow tests

To ensure that the model represents the actual distribution system, the model needs to be tested. Distribution system models are tested by

conducting flow tests, during which flows and pressures are measured. Pressure or, more appropriately, hydraulic head data collected from flow tests are then compared with the model output data. If the model output and field data are in acceptable agreement, the model can be used with confidence. If the model and field data do not agree, the model must be calibrated to come in acceptable agreement with the field data. Model calibration involves a reasonable adjustment of key unknown factors. For water quality models, the hydraulics portion of the model needs to be calibrated first, because the water quality calculations use the velocities generated by the hydraulic calculations.

Check other areas

To ensure that the model is fully calibrated, a second set of flow tests should occur in areas different than those areas tested in the initial calibration. The results should be compared with model predictions to ensure acceptable agreement. Further flow tests and calibration should be performed if the results do not agree well.

Using EPANET

To access EPANET, one must be in the WINDOWS program manager. If you are in MS-DOS, type WIN at the prompt. To open the EPANET program, double click on the EPANET icon in the WINDOWS program manager. At this point an input file needs to be opened. To open an input file, single click on the FILE menu and then single click on the desired input file to be opened. The input file will appear on the screen, but it cannot be edited using this window; therefore, it is best to close this window. Closing this window will not close the input file. To edit the input file, single click on edit and then single click on input; an edit window of the input file will appear. Below is a listing of input files given to Fort Monmouth staff.

File Name	Description
DAILY.INP	Daily Demand Fluctuations
QTEST1.INP	Flow Test 1
QTEST2T4.INP	Flow Tests 2 Through 4
QTEST5.INP	Flow Test 5

Different flushing simulations can be made by assigning flows to the desired nodes in the JUNCTIONS section of the input data. Flowed nodes can be chosen from the distribution model map in Figure 3. Also, initial conditions such as background demands in the JUNCTIONS section, initial chlorine concentrations in the QUALITY section, and decay rates in the REACTIONS section can be changed as needed.

Once values have been specified, a model simulation can be made. This is accomplished by clicking on the RUN menu, followed by another click on either windowed or minimized.

For a more detailed description of the use of EPANET, refer to the user's manual.

Plan Flushing

The calibrated model can be used as a tool for predicting when, where, and how long to flush from hydrants to increase chlorine concentrations to adequate levels. Model runs can be used to plan flushing only if field data such as initial source chlorine levels, initial source pressures, and initial fort chlorine levels are collected.

To use the model, measure existing conditions or estimate what they will be prior to flushing; estimate the flows that will occur; use demand multipliers for other flows; close pipes to simulate any closed valves; and run the model. Also, look at chlorine residuals at the flushed nodes and check velocities to see if either increases significantly.

6 Alternatives for Improving Water Quality

The following is an evaluation of alternatives for improving water quality at Fort Monmouth in terms of distribution system residual chlorine.

Do Nothing

Low chlorine residuals occur in the summer. Two alternatives to improve water quality are booster chlorination and flushing. Model simulations were made with and without booster chlorination over 1 week with a chlorine decay rate of 2 day^{-1} and 0.78 day^{-1}. For the simulations with booster chlorination, a chlorine concentration of 1 mg/L was used as the boundary chlorine concentration at Source C.

Plots of chlorine over time at selected nodes are presented in Figures 15-17 with and without chlorine feed at Source C. For the simulations without chlorine feed, chlorine levels varied only slightly over 12-hr intervals, and the residuals were at very low levels of 0.17 mg/L and less. Nodes 66, 63, and 58 are at increasing distances from Source C, and chlorine decreased with increasing distance from the source. Under normal use patterns contact times increase with increasing distances from the sources, causing a loss of disinfectant residual. The model shows that chlorine residuals might be increased by planned flushing, booster chlorination at Source C, or a combination of both alternatives.

Planned Flushing

Flushing can be used to increase chlorine levels at Fort Monmouth in summer months. However, in summer months, low source concentrations and high chlorine decay rates cause chlorine residuals to disappear within a few days. Maintaining chlorine levels throughout the summer will require repeated flushing. Determining when to flush should be based on a combination of chlorine level monitoring and modeling. The model could then be

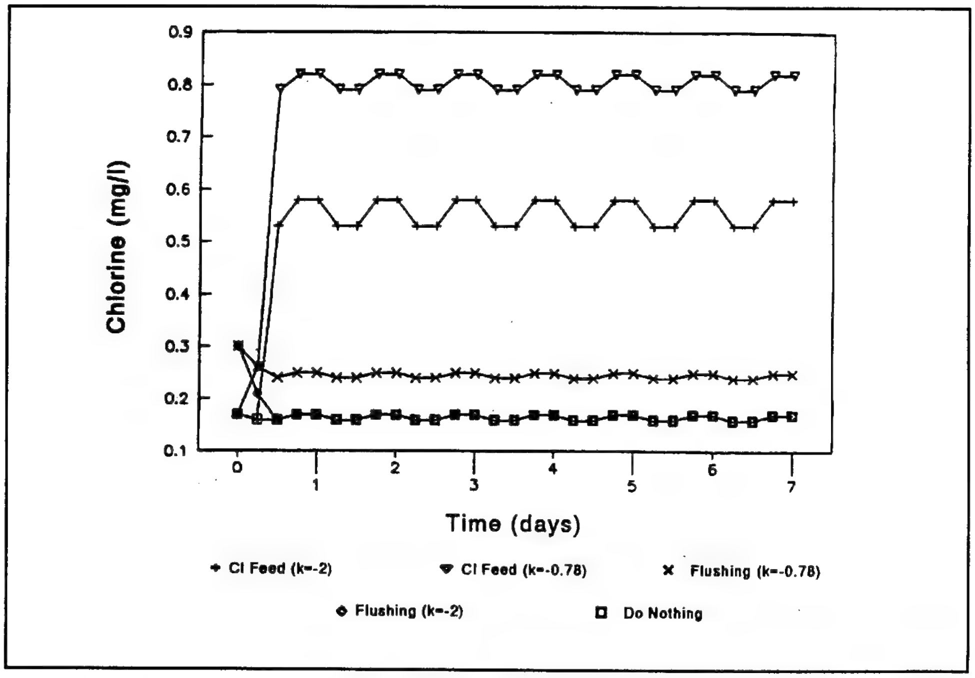


Figure 15. Chlorine concentration at Node 66 (near corner of Selfridge and Allen Avenues)

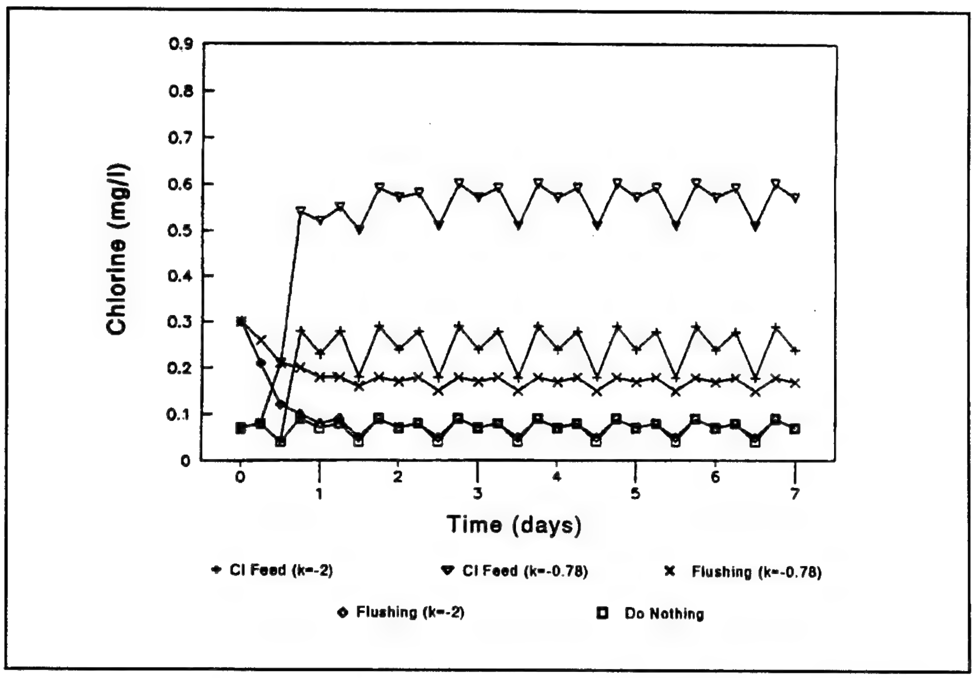


Figure 16. Chlorine concentration at Node 63 (near corner of Selfridge and Leonard Avenues)

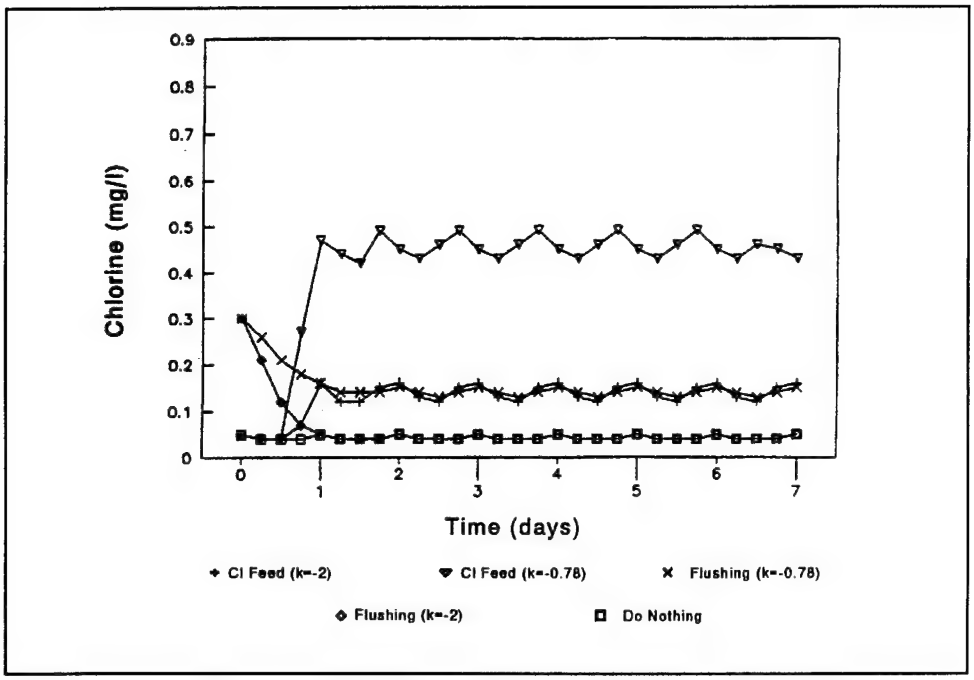


Figure 17. Chlorine concentration at Node 58 (near corner of Selfridge and Tilly Avenues)

used to simulate the chlorine die-off using the current-time water quality data. Such simulations will allow the determination of the optimal location and length of time of individual flushes. A flushing program would best be implemented in the summer months, when it would be most effective. The details of the directional flushing program conducted by the fort should be evaluated with the model to determine if improvements can be made to the program.

Install Chlorine Feed

Boosting chlorine residual at Source C during summer months can increase chlorine residuals at Fort Monmouth, as illustrated in Figures 15-17. The greatest increases in chlorine levels were predicted for areas closer to the source. However, significant increases in chlorine levels were seen at each node with booster chlorination.

Booster chlorination could occur by feeding one of three chemicals: chlorine gas, sodium hypochlorite, or calcium hypochlorite.

Chlorine gas. Chlorine gas feed is the least costly alternative when only the capital and operating costs are considered. However, the handling of chlorine gas involves costly regulatory requirements specified by the Occupational Safety and Health Administration (Process Safety Management Regulations), the EPA (Risk Management), and the state of New Jersey (similar to EPA's).

Sodium hypochlorite. Sodium hypochlorite feed would require more capital and operation expenses than gas feed. This type of feed system would also require more chemical storage space because sodium hypochlorite is an aqueous solution and is less concentrated than the other alternatives, making it more voluminous. The regulatory requirements for sodium hypochlorite feed are not as stringent as chlorine gas feed.

Calcium hypochlorite. Calcium hypochlorite feed would have the highest capital and operating expenses but would require less chemical storage space. Calcium hypochlorite is available as solid tablets and is the same material used for disinfecting swimming pools. Calcium hypochlorite has to be dissolved before it can be used as a disinfectant. This would require a tank and mixer and frequent addition of chlorine tablets into the tank. The regulatory requirements for calcium hypochlorite feed are the least costly.

The existing chlorine feed equipment at Fort Monmouth includes a chemical feed building, all necessary piping and connections, a chemical meter pump, and a tank. Preliminary equipment requirements for hypochlorite feed were discussed with Mr. Ken Cheatum of Wallace & Tiernan.

Flushing with Rechlorination

If the situation is such that chlorine levels become low in certain areas even with booster chlorination, flushing of such areas would be advisable. Again, for the most effective results, a combination of model simulations and water quality monitoring is required.

Evaluation of Alternatives

Given the low chlorine observed at Fort Monmouth and the results of the modeling, the "Do Nothing" alternative will not improve chlorine levels at the fort. Flushing increases chlorine residuals but the effects are short lived, with levels returning to those of the "Do Nothing" alternative after a few days. Observed chlorine decay is especially high in the summer as a result of higher water temperatures. This suggests that flushing, if used, is most effective in the summer months.

Even though there is some uncertainty in the chlorine decay rates, the only alternative that would ensure adequate chlorine levels at Fort Monmouth is rechlorination. There is hypochlorite feed equipment at Fort Monmouth. However, detailed engineering design, which was not in the scope of this project, is required to assess the steps necessary to make this equipment operable. The unit may only need to be operated during the summer months when chlorine die-off rates are greatest.

7 Summary

Model

The computer program EPANET was used to model the effectiveness of several alternatives for improving water quality in the Fort Monmouth distribution system. Model results show that hydrant flushing and/or booster chlorination at Source C can be used for this purpose. The model is a useful water quality management tool that can be used by the Fort Monmouth personnel to plan appropriate flushing and chlorine booster activities.

Model Calibration

The Fort Monmouth model was calibrated to make the results useful. However, further fine tuning of the model by Fort personnel is advised. This requires more flow tests with detailed pressure measurements that will allow such things as closed valves, capped pipes, and severely tuberculated pipes to be identified and accounted for by the model. Also, source chlorine concentrations in the NJA system should be monitored during the flow tests.

Technology Transfer

A copy of the EPANET program, input data, and the program user's manual was given to the staff at Fort Monmouth. Recommendations to the Department of Public Works on using EPANET at Fort Monmouth include using the model to:

- Help plan hydrant flushing based on current-time water quality data.
- Predict proper chlorine feed doses based on the chlorine levels and decay rates observed in the distribution system.

Recommendations

Rechlorination can increase chlorine levels at Fort Monmouth as shown by the EPANET model. Use of chlorine feed at Source C is recommended during warm weather.

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Appendix A
New Jersey American Water Quality Data

Table A1
Summary of NJA Water Quality Data

Compound	Maximum Contaminant Level	Range	Average
Primary Compounds			
Microbiological	1	0-0.1	0
Inorganic Chemicals, mg/L			
Arsenic	0.050	ND[1]-0.042	ND
Barium	1.000	ND-0.2	ND
Cadmium	0.010	ND-0.0016	ND
Chromium	0.050	ND-0.008	ND
Fluoride	4.0	--[2]	
Lead		ND-0.062	ND
Mercury	0.002	ND-0.0008	ND
Nitrate (as N)	10.0	ND-5.8	1.29
Selenium	0.010	ND-0.004	ND
Silver	0.050	ND-0.0006	ND
Organic Compounds, μg/L			
Pesticides (6)	0.2-100	ND	ND
Trihalomethanes (4)	100	--[3]	0.021
Benzene	1	ND	ND
			(Sheet 1 of 3)

[1] Not detected.
[2] Fluoride is added only in water supplied to customers in *Monmouth County*, at an average concentration of 1.0 part per million.
[3] Compliance is calculated on a running average of four quarterly samples.

Table A1 (Continued)			
Compound	**Maximum Contaminant Level**	**Range**	**Average**
Organic Compounds, $\mu g/L$ (Continued)			
Carbon tetrachloride	2	ND	ND
Chlordane	0.05	ND	ND
Chlorobenzene	4	ND	ND
ortho-Dichlorobenzene	600	ND	ND
meta-Dichlorobenzene	600	ND	ND
para-Dichlorobenzene	75	ND	ND
1,2-Dichloroethane	2	ND	ND
1,1-Dichloroethylene	2	ND	ND
1,2 Dicloroethylene	10	ND	ND
Methylene chloride	2	ND	ND
PCBs	0.5	ND	ND
1,1,1-Trichloroethane	26	ND-0.004	ND
Tetrachloroethylene	1	ND-0.121	ND
Trichlorobenzene	8	ND	ND
Trichloroethylene	1	ND-0.148	ND
Vinyl chloride	2	ND	ND
Xylenes	44	ND	ND
Secondary Compounds, mg/L			
Chloride	250	ND-103	17.24
Copper	1	ND-0.59	0.02
Fluoride	2	see note	
Hardness	250	ND-324	76.7
Iron	0.3	ND-1.1	0.05
Manganese	0.05	ND-1	0.05
Sodium	50	ND-47.5	20.06
Sulfate	250	ND-122	19.01
Total dissolved solids	500	32-323	114
Zinc	5	ND-0.4	0.1
Unregulated Compounds			
Inorganic Chemicals			
Alkalinity		ND-210	28.24
Aluminum		ND-062	0.053
			(Sheet 2 of 3)

Table A1 (Concluded)

Compound	Maximum Contaminant Level	Range	Average
Unregulated Compounds (Continued)			
Inorganic Chemicals (Continued)			
Antimony		ND	ND
Asbestos (million fibers/liter)		ND	ND
Beryllium		ND-2.1	ND
Boron		ND-2.3	ND
Calcium		ND-82.3	18.1
Cobalt		ND	ND
Magnesium		ND-37.84	5.05
Molybdenum		ND	ND
Nickel		ND-2.03	ND
Nitrate		ND	ND
Potassium		ND-10.7	3.8
Strontium		ND-4.6	0.25
Thallium		ND	ND
Vanadium		ND	ND
Organic Compounds			
Priority pollutants (131)		ND	ND
Radiological			
Radon (picocuries/liter)		0-879	312

(Sheet 3 of 3)

Appendix B
Results of Internal Roughness (C-Factor) Testing

Table B1
Internal Roughness Estimates

Location	Material	Diameter in.	Flow gpm	Head Loss ft	Length ft	C-Factor	Roughness Height, ft
Riverside Drive by DEH	CI	6	290	28	270	32	0.21
Cusselin Drive by NCO Housing	CI	6	237	60	700	30	0.24
Irwin Avenue	CI	6	314	76	400	25	0.32
Memories Lane by Theatre	CI	10	777	19	789	50	0.12

Appendix C
Model Input

Junctions

ID	Elevation	Demand (Pattern)	ID	Elevation	Demand (Pattern)
1	15	0	36	14	3
2	21	8	37	12	0
3	18	2	38	10	0
4	12	4	39	13	1
5	17	3	41	13	0
6	11	1	42	8	5
7	21	1	43	10	0
8	17	0	44	8	0
9	15	0	45	13	8
10	16	0	46	12	0
11	16	1	47	13	0
12	16	0	48	11	0
13	17	0	49	12	0
14	15	0	50	11	0
15	19	3	51	11	0
16	16	0	52	11	0
17	21	5	53	10	0
18	25	7	54	11	0
19	16	0	55	11	7
20	12	0	56	9	0
21	16	4	57	7	0
22	15	0	58	9	1
23	16	3	59	8	0
24	15	0	60	7	2
25	13	3	61	9	0
27	14	0	62	11	1
28	13	0	63	11	0
29	12	0	64	11	1
30	14	1	65	12	0
31	13	0	66	10	1
			67	7	0
33	20	0	68	7	1
34	13	3	69	11	1
35	16	0	70	11	0
71	8	0	204	7	0
72	10	0	205	8	0
73	9	0	206	8	0
74	15	1	207	22	0

(Continued)

ID	Elevation	Demand (Pattern)	ID	Elevation	Demand (Pattern)
75	17	0	208	15	0
76	16	0	209	26	0
77	20	1	210	14	0
78	21	4	211	18	0
79	20	2	212	26	1
80	18	5	214	16	1
81	22	5	215	22	0
82	23	6	216	15	0
83	27	6	217	16	0
84	20	8	218	18	1
85	20	0	219	15	0
86	14	0	220	20	0
200	16	0	221	24	0
201	9	0	222	4	0
202	9	0	223	11	0
203	8	0	224	8	0

Pipes

ID	Head Node	Tail Node	Length	Diameter	Roughness Coefficient	(Minor Loss Coefficient)	(Check Valve)
1	1	3	600	12	51		
2	2	3	130	8	45		
3	3	4	650	8	45		
4	2	5	1110	12	51		
5	5	6	640	12	51		
6	7	207	300	8	45		
7	8	7	450	8	45		
8	7	209	350	8	45		
9	217	9	270	6	40		
10	200	11	200	12	51		
11	10	216	100	8	45		
12	6	12	700	8	45		
13	12	13	190	8	45		
14	11	13	675	6	40		
15	11	14	450	12	51		
16	15	14	890	12	120		
17	14	16	755	6	120		
18	15	17	610	10	48		
19	80	81	400	10	120		
20	15	18	1650	10	48		
21	15	75	815	10	48		
22	20	76	750	8	45		
23	20	21	1020	8	45		
24	21	22	825	12	51		
25	23	24	830	6	40		
26	27	28	825	6	40		
27	29	30	850	8	45		
28	22	23	210	12	51		
29	23	28	280	8	45		
30	28	29	295	8	45		
31	23	31	200	12	51		
33	6	31	590	12	51		
34	21	24	215	12	51		
35	24	27	215	12	51		
36	27	30	245	12	51		
37	16	19	50	10	48		
38	25	33	960	6	40		
39	33	34	225	6	40		
40	30	36	1615	12	51		
41	34	35	755	6	40		
42	34	37	1075	6	40		
43	37	38	890	6	40		
44	69	73	1415	6	40		
45	36	42	1315	8	45		
46	35	36	65	12	51		
47	35	41	700	12	51		
48	35	39	290	6	40		
49	39	65	1130	6	40		
50	29	69	215	8	48		
51	41	43	655	12	51		
52	24	25	85	6	40		
53	42	43	210	6	40		
54	41	45	870	6	40		
55	39	45	1110	6	40		
56	45	46	65	6	40		
57	43	44	410	12	51		
58	44	68	700	10	48		

(Continued)

ID	Head Node	Tail Node	Length	Diameter	Roughness Coefficient	(Minor Loss Coefficient)	(Check Valve)
59	67	68	80	6	40		
60	66	67	420	6	40		
61	65	66	370	6	40		
62	64	65	950	6	40		
63	63	66	805	6	40		
64	62	67	775	6	40		
65	61	68	825	10	48		
66	61	62	495	8	45		
67	63	223	220	8	45		
68	63	64	225	8	45		
69	52	64	265	8	45		
70	57	70	550	6	40		
71	51	55	400	6	40		
72	51	52	220	8	45		
73	56	57	220	6	40		
74	54	55	220	8	45		
75	56	71	780	6	40		
76	53	54	625	8	45		
77	38	53	330	8	45		
78	48	53	690	8	45		
79	48	49	150	8	45		
80	49	54	400	6	40		
81	50	51	150	8	45		
82	49	50	75	8	45		
83	46	48	310	8	45		
84	47	50	220	6	40		
85	46	47	245	6	40		
86	43	47	1180	6	40		
87	57	205	210	6	40		
88	58	224	220	8	45		
89	59	62	640	8	45		
90	59	60	530	8	45		
91	60	72	580	6	40		
92	52	70	160	8	45		
93	53	71	275	4	40		
94	61	72	310	6	40		
95	38	73	235	6	40		
96	86	208	460	8	45		
97	19	75	1675	10	45		
98	16	76	115	8	45		
122	16	22	950	12	51		
142	37	46	590	6	40		
155	55	56	300	6	40		
165	74	210	150	8	45		
166	5	77	800	8	45		
167	77	78	750	8	45		
168	78	79	810	8	45		
169	79	1	1200	8	45		
171	81	18	50	10	120		
172	18	82	1350	8	45		
173	82	83	400	8	45		
174	83	84	400	8	45		
175	84	85	400	8	45		
176	17	80	400	10	120		
177	83	81	1000	8	45		
178	84	80	1000	8	45		
179	85	17	1000	8	45		
180	74	86	620	8	45		
181	86	211	150	8	45		

(Continued)

ID	Head Node	Tail Node	Length	Diameter	Roughness Coefficient	(Minor Loss Coefficient)	(Check Valve)
182	87	44	150	12	51	157	CV
200	10	200	160	12	120		
201	201	202	210	6	40		
202	202	203	130	6	40		
203	203	204	200	6	40		
204	204	205	230	6	40		
205	205	206	150	6	40		
206	205	201	220	6	40		
207	58	201	120	6	40		
208	63	58	620	6	40		
209	207	74	400	8	45		
210	208	6	180	8	45		
212	209	212	360	8	45		
214	210	214	360	8	45		
215	211	215	360	8	45		
216	212	9	150	8	45		
217	214	10	100	8	45		
218	215	12	100	8	45		
219	216	12	540	8	45		
220	200	217	420	6	40		
221	214	218	320	6	40		
222	218	215	320	6	40		
223	212	214	720	6	40		
224	209	210	720	6	120		
225	210	211	650	6	120		
226	219	8	5	6	40	50	CV
227	220	1	5	6	40	90	CV
228	219	221	2650	10	2000		
229	221	220	1800	10	2000		
230	220	222	2500	10	2000		
231	222	87	2800	36	2000		
232	223	224	650	6	40		
233	223	62	200	8	45		
234	224	59	200	8	45		

Tanks

ID	Elevation	Initial Level	Minimum Level	Maximum Level	Diameter	(Minimum Volume)
87	158					

Status

First Link	(Last Link)	Setting
15		CLOSED

Quality

First Node	(Last Node)	Initial Quality
87	0.18	
219	0.18	
220	0.18	
221	0.18	
222	0.18	

Sources

Node	Concentration	(Pattern)
87	0.40	
219	0.18	6
220	0.18	6

Reactions

Type	(First ID)	(Last ID)	Coefficient
Global Bulk			-2.0

Appendix D Discussion of QA/QC Test Results

Since the chlorine levels measured in the field were all relatively low, there was a concern that these results might not be valid. Testing was performed to check the validity of field data results. Three tests were performed.

For Test 1, three samples were measured for chlorine. Chlorine was measured for each side of the cuvette. A total of 12 measurements were made. Table D1 shows that cuvette rotation is a minor source of error.

In Test 2, old and new reagents were compared (Table D2). One large sample was taken. Six smaller samples were taken from the larger sample and tested for chlorine using old and new reagent packets. In this case, the age of reagent had little interference on the field test results.

Test 3 tested the portable HACH kit (which was an analog type) against a stationary HACH kit (which was digital). Three samples were measured for chlorine. The differences in measurements for both machines were negligible (Table D3).

Table D1
Test 1, Cuvette Rotation (rotation to the right)

Blank Side	Cl (mg/L)	Sample Side	Cl (mg/L)
Sample 1			
1	0	1	0.44
		2	0.44
		3	0.44
		4	0.44
2	0	1	0.44
		2	0.44
		3	0.44
		4	0.44
3	0	1	0.44
		2	0.44
		3	0.44
		4	0.44
4	0	1	0.44
		2	0.44
		3	0.44
		4	0.44
Sample 2			
1	0	1	0.45
		2	0.45
		3	0.45
		4	0.45
2	0	1	0.45
		2	0.45
		3	0.45
		4	0.44
3	0	1	0.44
		2	0.44
		3	0.44
		4	0.44
4	0	1	0.44
		2	0.44
		3	0.44
		4	0.44

(Continued)

Table D1 (Concluded)			
Blank Side	**Cl (mg/L)**	**Sample Side**	**Cl (mg/L)**
Sample 3			
1	0	1	0.45
		2	0.45
		3	0.45
		4	0.45
2	0	1	0.45
		2	0.45
		3	0.45
		4	0.45
3	0	1	0.45
		2	0.44
		3	0.44
		4	0.44
4	0	1	0.44
		2	0.44
		3	0.44
		4	0.44

Table D2
Test 2, Comparing Reagents of Different Ages

Sample No.	Cl Concentration (mg/L)	
	Old Packets	New Packets
4	0.45	0.45
5	0.45	0.46
6	0.43	0.43

Table D3
Test 3, Comparing Analog and Digital Spectrophotometers

Sample No.	Cl Concentration (mg/L)	
	Analog	Digital
7	0.44	0.44
8	0.46	0.46
9	0.46	0.45

Appendix E
Chlorine Flow Test Data

Table E1
Results of Chlorine Flow Tests

Test	Test Node	Flow, gpm	Time, min	Chlorine, mg/L
1	206	528	0	0.00
			4	0.00
			8	0.00
			12	0.02
			17	0.04
			23	0.03
			27	0.00
			37	0.00
			42	0.00
			49	0.00
			54	0.00
			60	0.00
			68	0.00
			71	0.00
2	7	973	0	0.00
			2	0.00
			6	0.14
			8	0.05
			10	0.09
			12	0.13

(Sheet 1 of 3)

Table E1 (Continued)

Test	Test Node	Flow, gpm	Time, min	Chlorine, mg/L
			13	0.13
			15	0.15
3	212	973	0	0.05
			2	0.05
			5	0.05
			8	0.03
			10	0.00
			12	0.00
			15	0.00
			17	0.00
			19	0.00
			21	0.00
			26	0.01
			29	0.03
			32	0.03
			35	0.05
			38	0.00
			40	0.00
			43	0.10
			47	0.05
			51	0.07
			56	0.00
			60	0.05
			64	0.03
			67	0.03
4	214	868	0	0.03
	218	638	3	0.03
			6	0.14
			10	0.03
			13	0.05

(Sheet 2 of 3)

Table E1 (Concluded)				
Test	**Test Node**	**Flow, gpm**	**Time, min**	**Chlorine, mg/L**
			15	0.06
			19	0.15
			21	0.15
			25	0.20
			28	0.20
			33	0.20
			36	0.20
			41	0.15
			45	0.15
5	206	514	0	0.00
			4	0.05
			7	0.05
			10	0.08
			14	0.00
			18	0.00
			22	0.00
			28	0.05
			31	0.03
			35	0.03
			41	0.05
			44	0.06
			49	0.00
			54	0.05
			57	0.03
			62	0.01
			72	0.05
				(Sheet 3 of 3)

Appendix F
Initial Calibration Data

Table F1
Initial Calibration Results

Test No.	Node	Flow, gpm	Field HGL,[1] ft	Model HGL, ft
1	72	914	55	70
2	75	1,621	51	96
3	76	1,340	108	123
4	23	1,772	98	135
5	74	1,864	58	88
6	73	670	89	105

[1] Hydraulic grade line.

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Under the Facilities Engineering Applications Program, the U.S. Army Corps of Engineers wanted to test the capability of the EPANET computer model for evaluating water quality in water distribution systems. Fort Monmouth, New Jersey, has experienced low chlorine residuals levels. The EPANET model was calibrated using hydrant flow tests to predict chlorine die-off in the distribution system at the Fort. The model was then used to compare the effects of flushing and chlorine addition to improve water quality. Because of the high chlorine die-off rates in warm weather, it appears that chlorine addition is the only way to significantly improve chlorine residuals during summer months.

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